# The 16-day variation in tidal amplitudes at Grahamstown (33.3° S, 26.5° E)

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**Abstract.** Meteor wind data at Grahamstown (33.3° S, 26.5° E) have been used to study the short-term (planetary scale) variations of the diurnal and semidiurnal tidal amplitudes at $\sim 90$ km altitude. Wavelet multi-resolution and spectral techniques reveal that planetary periodicities of $\sim 10$ and $\sim 16$ days dominate the wave spectrum in the $\sim 2$–20-day period range. The quasi-16-day oscillation is thought to be related to similar oscillations in the lower atmosphere. Also, there seems to be a link between the winter/equinox 16-day oscillation in the mean flow and that in the semidiurnal tidal amplitudes. It is thought that this is probably due to either the coupling between the normal mode-mean flow interactions and the gravity wave-tidal interactions, or to direct nonlinear interactions between planetary waves and the tide. On the other hand, a comparison of the mean flow and the diurnal tide does not show evidence of correlation. Possible reasons for this disparity are discussed briefly.

**Key words.** Meteorology and atmospheric dynamics (waves and tides)

## 1 Introduction

In an earlier paper (Malinga and Poole, 2002, which will be referred to as Paper 1), we considered the short-term variations of the mean flow with special emphasis on the quasi-16-day oscillation. In this paper we study similar variations in the diurnal and semidiurnal tidal amplitudes.

In general, tides show great variability on day-to-day time scales (e.g. Charles and Jones, 1999). The source of these short-term variations in tides is not fully understood. There could be several mechanisms involved which could act together or independently (Teitelbaum and Vial, 1991), but the extent of the contribution of each of these is not known (Vial et al., 1991).

One mechanism involves the variation of tidal forcing due to the variations in water vapour, cloud cover (Vial et al., 1991) and ozone (Bernard, 1981). Changes in background propagation conditions could also be relevant. Bernard (1981) pointed out that classical theory indicates that tidal amplitudes and phases (in particular) are very sensitive to propagation conditions. Rapid variation in the wind and temperature may result in partial tidal reflections. This is closely related to the suggestion by Poulter (1980) that temperature discontinuities and negative temperature gradients cause partial or total reflection of tidal modes. These reflected modes can, in turn, result in a change in the tidal structure through mode superposition which, as indicated by Forbes (1990) and Vial and Teitelbaum (1984), can change the tidal structure considerably on a day-to-day basis, even if the phase shifts between the modes are small (1–2 h). Another possible mechanism is the injection of energy near tidal frequencies due to local or synoptic scale fluctuations (Vial et al., 1991). While any of the above mechanisms might play a part, most work on tidal variability has concentrated on gravity wave-tidal interactions (e.g. Walterscheid, 1981; Fritts and Vincent, 1987; Forbes et al., 1991; Wang and Fritts, 1991; Lu and Fritts, 1993; Liu et al., 2000), and direct nonlinear interaction between planetary waves and tides (e.g. Teitelbaum and Vial, 1991; Clark and Bergin, 1997; Kamalabadi et al., 1997; Beard et al., 1999; Pancheva, 2000). These mechanisms will be discussed further in the context of our observations.

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## 2 Results

Figures 1 and 2 show, respectively, the short-term fluctuation of diurnal and semidiurnal tidal amplitudes which, as in the case of the mean wind (Paper 1), are superimposed on long-term trends to be explored in detail elsewhere. These amplitudes were deduced by the harmonic analysis of hourly averages of horizontal wind velocities covering a 4-day data window. This 4-day data window was advanced 1 day at a time and the amplitude of the data window was attributed to the second day of the interval.

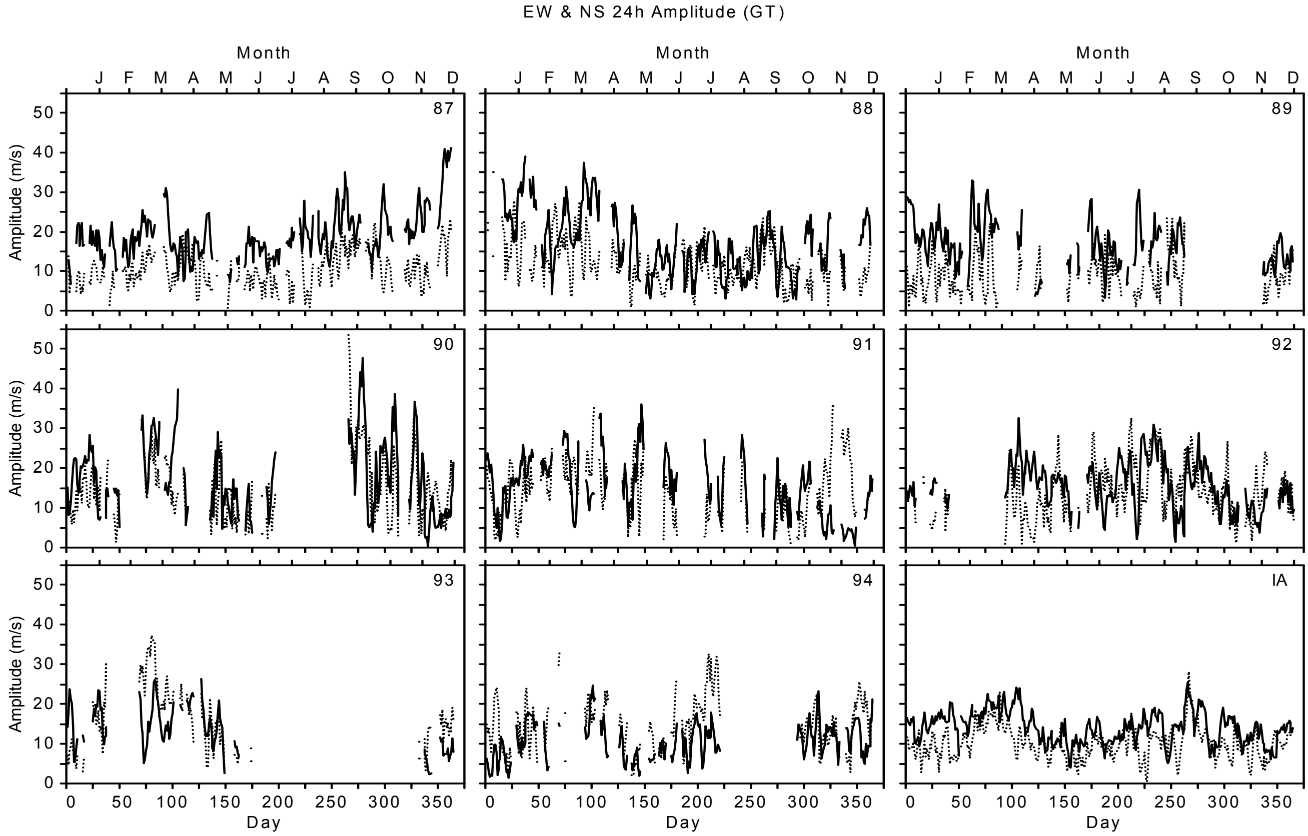


**Fig. 1.** The zonal (solid line) and the meridional (dotted line) amplitudes of the diurnal tide for the years 1987–1994 and for the corresponding 8-year interannual average (IA) for Grahamstown.

### 2.1 Planetary scale variations

The possible role of gravity waves in producing these variations has been given considerable attention. Upward propagating gravity waves are thought to encounter a total wind field that consists of the mean flow and tidal wind, and is, therefore, temporal. Fritts and Vincent (1987) developed a model to help investigate the effects of the different environments on the propagation and saturation of high-frequency (period $< 1$ h) gravity waves. Their model predicts that in an environment where $\overline{u} - c$ (see Paper 1) increases with height the gravity wave amplitude and the momentum flux should also increase. At the region where the above growth stops, a large momentum flux divergence and an acceleration of the mean flow are expected. These authors found that this tidally linked mean flow acceleration generates a nontidal (i.e. not thermotidally excited) "tide", with a phase advance of $\sim 6$ h compared to the thermal tide. As a result of this "tide", the apparent tide is advanced in phase and altered in amplitude compared to the thermal tide (Fritts and Vincent, 1987).

While there is agreement on the phase advance, different views have been expressed regarding amplitude alterations. Contrary to the amplitude reduction suggested by Fritts and Vincent (1987), analytic model results by Lu and Fritts (1993) predict an enhancement of apparent tidal amplitudes, although these results were sensitive to other factors that were not investigated in detail. The calculations of Lu and Fritts (1993) show that the gravity wave forcing of tides may be very variable, with a dependency on the tidal environment and the characteristics of the gravity wave spectrum being modulated. These authors also concluded that whether gravity wave forcing results in amplitude decreases (e.g. Fritts and Vincent, 1987; Forbes et al., 1991) or increases (e.g. Wang and Fritts, 1991) depends on the details of the tidally modulated filtering of gravity waves. In fact, Walterscheid (1981) mentions that the strength of such forcing depends on the intensities, phase velocities and the coherence of these waves and may exhibit substantial day-to-day variability.

Planetary waves in the zonal circulation can also interact directly with vertically propagating tides, particularly the semidiurnal (Pancheva, 2001). Any nonlinearity in this interaction could result in modulation of tidal amplitudes. Such a mechanism can be revealed through bispectral analysis (e.g. Clark and Bergin, 1997; Pancheva, 2000) or the presence of the sum and/or difference frequencies in the tidal spectrum due to "secondary waves", resulting from the interaction (e.g. Teitelbaum and Vial, 1991). In the latter case the diagnosis could evidently be strengthened by comparison of the phases of the tidal, planetary and secondary waves to detect quadratic phase coupling (Nikias and Raghuveer, 1987).

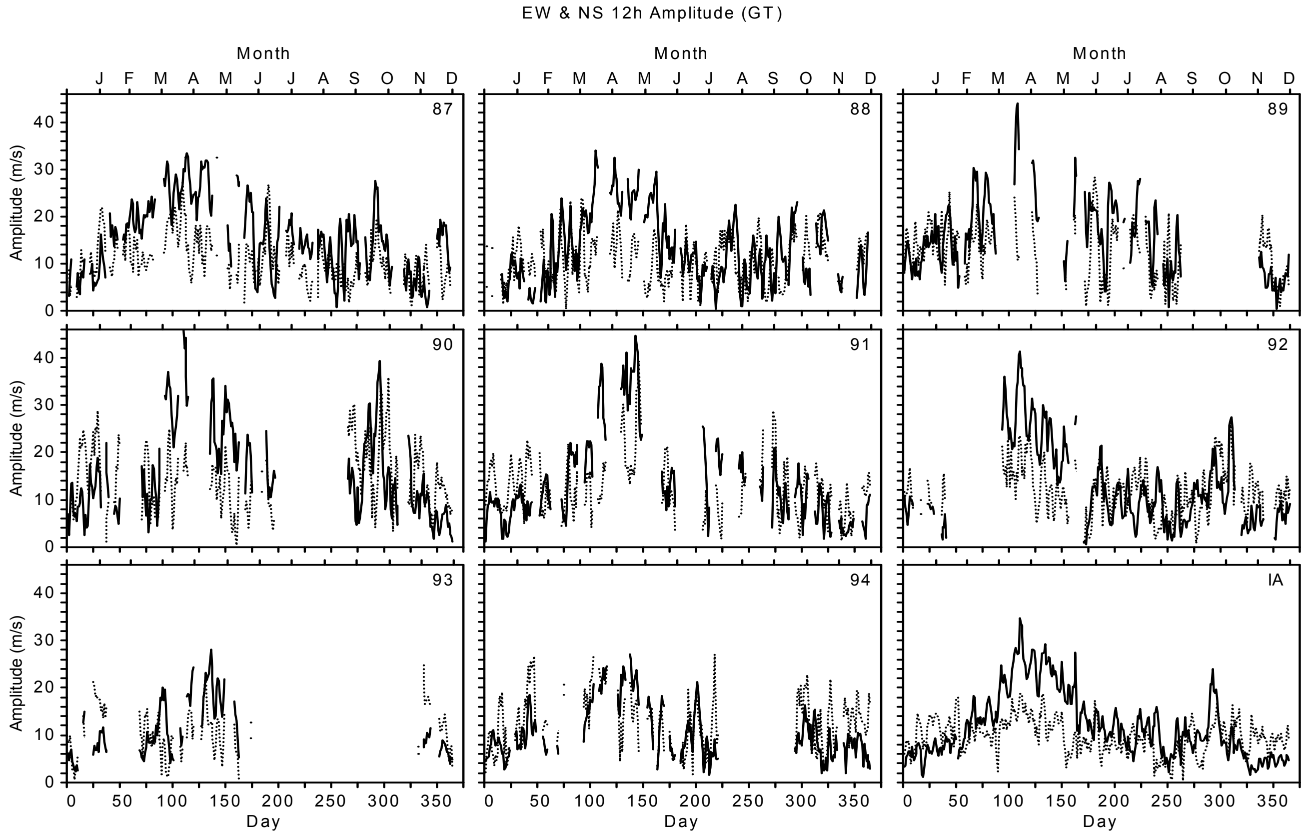


**Fig. 2.** The zonal (solid line) and the meridional (dotted line) amplitudes of the semidiurnal tide for the years 1987–1994 and for the corresponding 8-year interannual average (IA) for Grahamstown.

### 2.2 The 16-day oscillation

Figures 3 and 4 reveal a more detailed structure of the planetary scale variation of the diurnal and semidiurnal amplitudes, respectively. These figures show the multi-resolution and spectral analysis of the mean-corrected tidal amplitudes at Grahamstown. As in Paper 1, the top row of panels in these figures represents the zonal ($u$, black line) and the meridional ($v$, red line) mean-corrected amplitudes (after data gaps had been linearly interpolated). In rows 2 to 5 and starting from the left, the first column of panels show the low-frequency approximations ($A_m$) for levels m starting from 1 to 4. The finer resolution details ($D_m$) are shown in the second column. The ranges of the scale $s$ for the approximations and details are also shown. Further particulars about these figures can be found in Paper 1.

The spectra of the details at different levels (third and fourth columns) show that there are spectral components with periods of $\sim$ 2–3 days, $\sim$ 7–8 days, $\sim$ 10 days and $\sim$ 16–20 days. Although some strong components have periods $>$ 20 days, our focus in this paper is on those components within the $\sim$ 2–20-day period range. In this range the dominant components are those associated with 16-day and $\sim$ 10 day periods. As was the case with the mean flow (Paper 1), the spectra of the details show that the zonal planetary activity is not necessarily correlated to its meridional counterpart.

In Paper 1 we observed that the 16-day oscillation dominated the planetary scale wave spectrum of the mean flow. A question that comes to mind is whether the 16-day oscillation in the tidal amplitudes is related to that in the mean flow or not. Such a link could be due to the coupling between the normal mode-mean flow interactions (Paper 1) and gravity wave-tidal interactions. The 16-day modulation of the mean flow by Rossby-gravity normal modes could result in a similar modulation of the mean flow filtering effects and hence, that of the spectrum of the transmitted gravity waves (see Paper 1 and references therein). Since gravity wave-tidal interactions depend on the spectrum of the interacting gravity waves, we might expect a 16-day modulation of gravity wave-tidal interactions that will manifest itself in the tidal amplitudes. This type of modulation could also arise through direct, nonlinear interactions between planetary waves and tides, as discussed in Sect. 2.1. In either case, we would expect some correlation between the 16-day oscillation in the mean flow and in the tides.

To investigate the above suggestions we have compared the 16-day oscillation of the mean flow with that of the tides (Figs. 5 and 6). A comparison of the wavelet spectrum of the zonal mean flow with that of the semidiurnal tidal amplitudes (Fig. 6) in the vicinity of the period of 16-days suggests a correlation in June/July 1987, May/June 1988 and

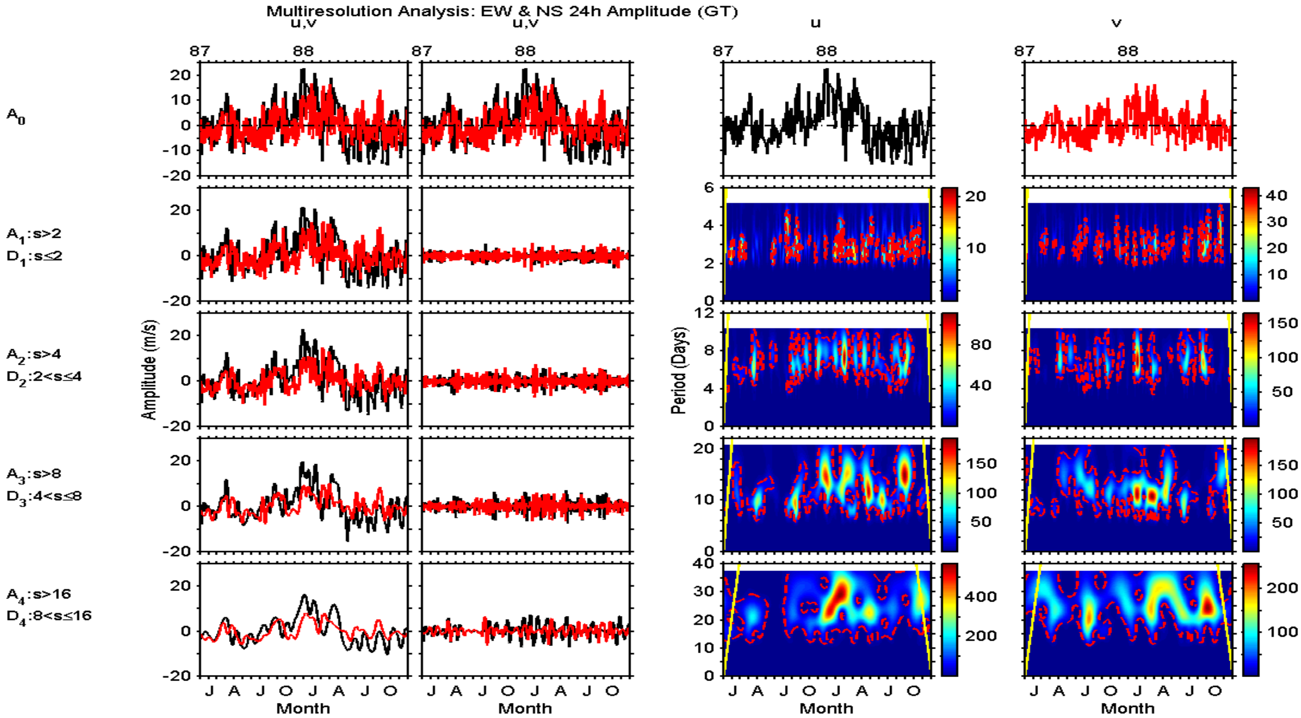


**Fig. 3.** Analysis of the diurnal tide at Grahamstown: Top row, the original signal $A_o$. Rows 2–5, starting from the left, show (1st column) the approximations ($A_m$ where $m$ is the level), (2nd column) the details ($D_m$), (3rd column) the spectrum of the zonal details and (4th column) the spectrum of the meridional details. The black and red time series lines represent the zonal ($u$) and meridional ($v$) amplitudes, respectively. The scale ($s$) ranges are shown on the left. The units of the colour bars are arbitrary.

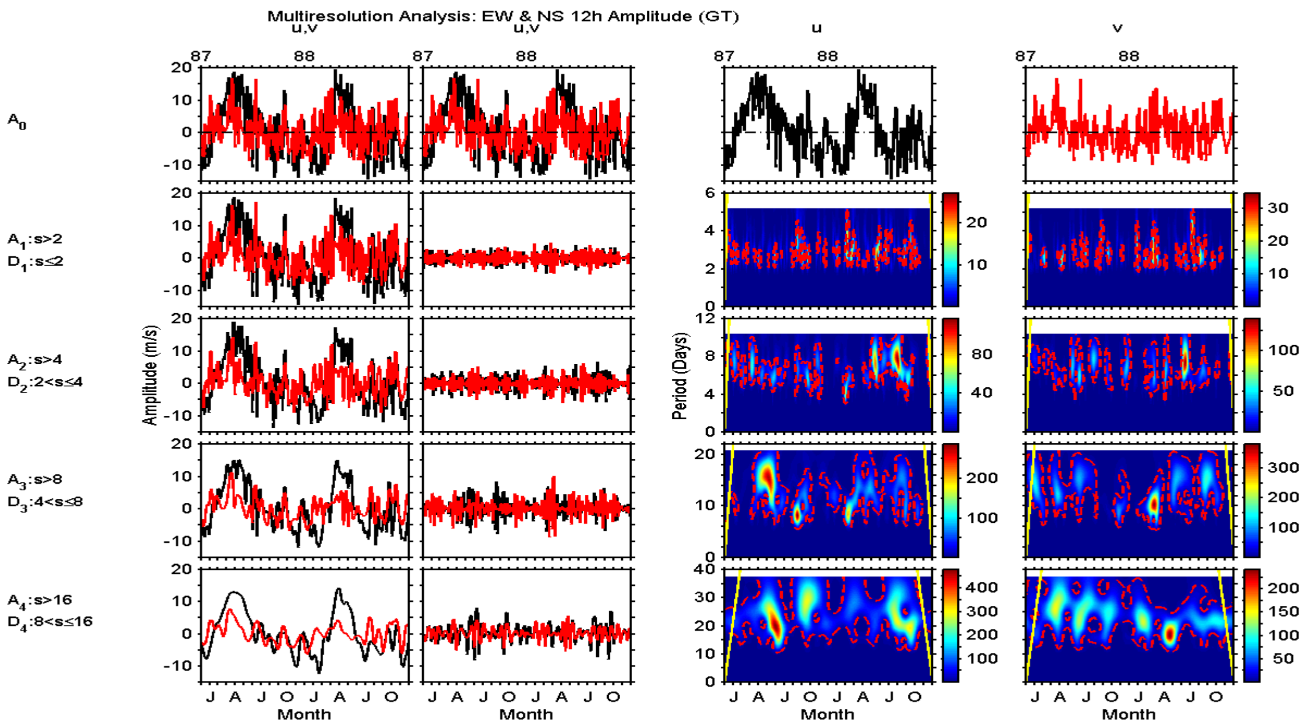


**Fig. 4.** Analysis of the semidiurnal tide at Grahamstown: Top row, the original signal $A_o$. Rows 2–5, starting from the left, show (1st column) the approximations ($A_m$ where $m$ is the level), (2nd column) the details ($D_m$), (3rd column) the spectrum of the zonal details and (4th column) the spectrum of the meridional details. The black and red time series lines represent the zonal ($u$) and meridional ($v$) amplitudes, respectively. The scale ($s$) ranges are shown on the left. The units of the colour bars are arbitrary.

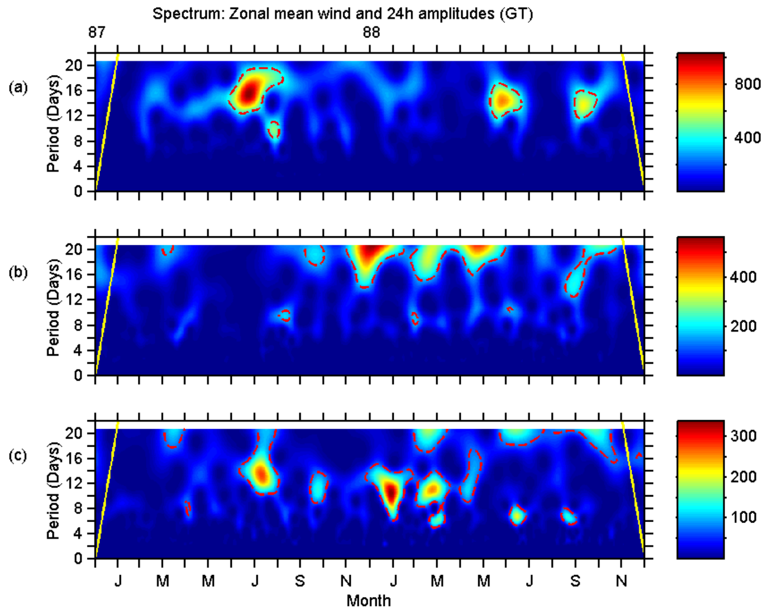


**Fig. 5.** The wavelet spectrum of **(a)** the zonal mean wind, **(b)** the zonal amplitudes of the diurnal tide and **(c)** the meridional amplitudes of the diurnal tide at Grahamstown.

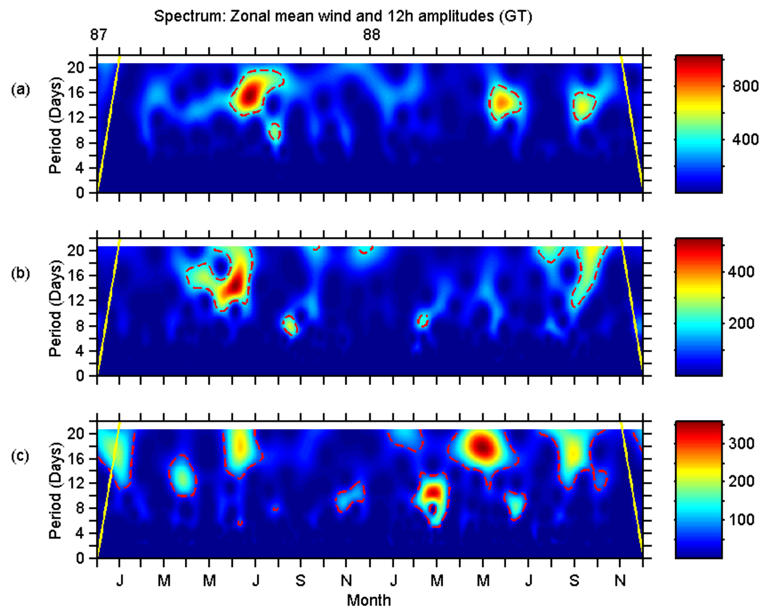


**Fig. 6.** The wavelet spectrum of **(a)** the zonal mean wind, **(b)** the zonal amplitudes of the semidiurnal tide and **(c)** the meridional amplitudes of the semidiurnal tide at Grahamstown.

September/October 1988. From this figure we can clearly see the dominance of the 16-day oscillations in winter and the equinoxes for the mean flow and the semidiurnal tide. However, a similar comparison for the diurnal tide does not generally show clear correlations, except for a strong winter event in the meridional tide in 1987 (Fig. 5c). More typically, the diurnal tide shows some tendency towards significant 16-day oscillations in the summer, uncorrelated with mean flow behaviour.

The differences in the modulation of the two tides are not readily explained in terms of gravity wave interactions, although the conclusion of Lu and Fritts (1993) that gravity wave forcing of tides depends inter alia on the tidal environment (see Sect. 2.1) does raise the possibility that differences in the temporal structure of the two tides (compare Figs. 1 and 2) may result in different responses to a given set of gravity waves.

The possible role of nonlinearity has been addressed by examination of complex (amplitude and phase) spectra covering 32-day intervals coinciding with the 16-day wave events discussed above. There are some signs of nonlinear interaction between planetary waves and the zonal component of the semidiurnal tide, as indicated by the presence of some activity at the planetary wave frequency, as well as satellite spectral lines (secondary waves) at the sum and difference frequencies near 2.0 cpd, but the corresponding phase comparisons are inconclusive. Nonlinear interactions are not at all evident in the complex spectra of the meridional component of the semidiurnal tide or in either component of the diurnal tide. Such disparities in the tidal response to planetary waves have been reported by others (e.g. Beard et al., 2001), and could be associated with the filtering of upwardly propagating planetary and/or secondary waves from interactions that have taken place below the volume of observation.

There appears to be no conclusive method of deciding between mechanisms that might influence tidal variability; in general, several could be involved. Correlative studies between gravity wave activity in the troposphere/stratosphere regions and MLT signatures could be useful here, but the necessary data for this sector are not available.

## 3 Summary

As in Paper 1, the use of wavelet techniques has facilitated the exploration of planetary scale fluctuations, here with reference to tidal amplitudes. Again, these variations are superimposed on seasonal trends. The observed planetary scale wave spectrum is found to be dominated by the 10- and 16-day oscillations. The planetary oscillations of the zonal component are not necessarily correlated with those of its meridional counterpart. In Paper 1 we observed that the 16-day oscillation tends to dominate the planetary range spectrum of the mean flow, leading us to investigate a possible link with the tidal 16-day oscillations found here. Such a link is observed, particularly in the case of the semidiurnal tide, and is most likely due to the coupling between the normal mode-mean flow interactions and the gravity wave-tidal interactions and/or direct nonlinear planetary wave-tidal interactions.

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